Response of Thinned, Immature Lodgepole Pine to Nitrogen Fertilization: Three-year Growth Response

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EXECUTIVE SUMMARY

This report documents the response of 11 young (15- to 25-year-old), thinned lodgepole pine stands to nitrogen fertilization, 3 years after treatment. Growth response was analyzed in two ways: individual-tree response and land-area response. Treatment effects on growth of trees in different diameter classes and on growth of the largest 50% and 580 stems per hectare are also reported.

Nitrogen fertilization has, 3 years after treatment, increased basal area and volume increment on both an individual-tree and land-area basis. Tree volume response averaged 31% (range 18-55%) and 35% (range 15-61%) for applications of 100 and 200 kg N/ha, respectively. On a stand-volume basis, however, the favourable effects of fertilization were partially negated by treatment-related damage and mortality (i.e., red squirrel feeding injuries and snowpress). In the absence of damage, nitrogen fertilization improved net volume growth by as much as 6.7 m^3/ha over a 3-year period.

Application of 200 kg N/ha generally resulted in small incremental gains over an application of 100 kg N/ha. However, as time since treatment progresses, the dosage effect may increase because of a more sustained response to the higher nitrogen application rate.

Improved palatability and nutritive quality significantly increased the susceptibility of fertilized lodgepole pine to feeding attacks by red squirrels. Notwithstanding outright mortality, semi-girdling (sub-lethal) injury to crop trees apparently partially negates the beneficial effects of nitrogen additions and may have a negative impact on subsequent yield and investment value. Because the probability of girdling is inversely related to stem diameter, squirrel damage generally had a greater negative impact on stands thinned at the time of fertilization (due to a smaller average crop tree diameter) than in adjacent, previously thinned stands. The best method for preventing or minimizing red squirrel feeding injuries is to confine operational fertilization to stands having a low hazard rating (based on a pre-treatment damage survey). Fertilization of high risk stands should be delayed until crop trees are large enough to withstand damage wounds. The development of squirrel damage in operationally fertilized stands should be monitored over time.

Whereas absolute volume gains were generally greater in installations thinned prior to fertilization (primarily attributable to their larger initial dbh), growth relative to unfertilized trees was larger in stands thinned at the time of fertilization. Moreover, 3-year height response data indicate that fertilization at the time of thinning may reduce the impact of "thinning shock" in lodgepole pine. Unfortunately, fertilization increases the susceptibility of recently thinned stands to snowpress damage, especially on responsive sites. Results indicate that snowpress damage can be avoided by delaying fertilization until 2 or 3 years after thinning. This adjustment period, as well as minimizing snowpress damage, will also enable red squirrel damage potential to be more fully evaluated before operational fertilization investment decisions are made.

Graphical diagnosis of shifts in needle weight and foliar nutrient concentration and content in the first growing season following fertilization generally corresponded with subsequent 3-year volume response. Therefore, where fertilizer screening trial response data are available, the foliar graphical diagnostic technique may represent a reasonably accurate "quick index" for evaluating the long-term volume response potential of candidate stands. The technique may also provide rapid feedback regarding the relative responsiveness of operational blocks to aerial fertilization and may, in some cases, at least partially satisfy operational fertilization monitoring objectives.

Response to nitrogen fertilization was variable and the nitrogen status of a site was shown to be an unreliable predictor of the potential responsiveness to nitrogen application. From the 11 fertilizer trials reported here, it is not possible to adequately explain this variation in response. A great deal more research is needed to identify and test relationships between various stand and site characteristics, nutrient deficiencies, and response to fertilizer treatments, before site-specific guidelines for lodgepole pine operational fertilization decision-making can be developed. However, foliar nutrient concentration data indicate that reserves of nutrients other than nitrogen, although generally adequate to balance native supplies of nitrogen, may sometimes be inadequate to sustain or enhance growth following nitrogen fertilization. Specifically, boron and/

or sulphur deficiencies, either induced or aggravated by nitrogen additions, may limit growth response on some sites and may also partially explain the small incremental gains achieved between 100 and 200 N in other installations. More research is needed to accurately assess the boron and sulphur status of interior forests. Inferred nutrient deficiencies must be systematically tested in fertilizer trials using various rates and combinations of the supposedly deficient nutrients. Until research data indicate otherwise, it is recommended that sulphur continue to be added in conjunction with nitrogen when forests within the interior plateau are operationally fertilized. In addition, boron should be added to the nitrogen/sulphur mix in areas where average pre-fertilization foliar boron concentrations are below 10-15 ppm.

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1 INTRODUCTION

Lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) is an extremely important commercial tree species in British Columbia. Only interior spruce (*Picea glauca* [Moench]) Voss and *Picea engelmannii* Parry, or the naturally occurring hybrid of these species) contributes a greater amount than lodgepole pine to the provincial harvest (B.C. Ministry of Forests 1984). Immature stands of lodgepole pine occupy approximately 20% (8.1 million ha) of the total productive forest land in the interior of the province (B.C. Ministry of Forests 1980). Intensive management of these immature stands may be the key to assuring future wood supplies in many Timber Supply Areas.

The ability of lodgepole pine to respond favourably to thinning is well documented (Johnstone 1985; Johnstone and Cole 1988). By redistributing the available growing space, thinning reduces inter-tree competition and concentrates growth on fewer crop trees, with the ultimate objective of increasing the future yield and/or value of merchantable wood from the stand. Response potential is generally greatest in young stands that have not yet experienced severe growth repression. Although few in number, research studies indicate lodgepole pine may also be responsive to fertilizer application (Malm 1973; Boyd and Strand 1975; Cochran 1975, 1979; Bella 1978; Cochran *et al.* 1979; McIntosh 1982; Weetman and Fournier 1982; Pettersson 1984; Yang 1985*a*, 1985*b*). Also, generally positive results have been reported for fertilization trials with semi-mature jack pine (*Pinus banksiana* Lamb.) in eastern Canada (Morrison *et al.* 1976; Krause *et al.* 1982; Groot *et al.* 1984; Weetman and Fournier 1984*a*, 1984*b*; Weetman *et al.* 1987). In fact, the relative responsiveness of jack pine — a species that is ecologically similar to, and interbreeds with, lodgepole pine (Critchfield 1980) — is ranked high compared to other species (Foster and Morrison 1983).

Results from a large number of fertilization research trials in Scandinavia and North America indicate that nitrogen is the element that most limits the growth of northern temperate and boreal forests growing on mineral soil within the glaciated region (Armson *et al.* 1975; Gessel *et al.* 1979; Krause *et al.* 1982; Foster and Morrison 1983; Möller 1983*a*). The responsiveness of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) in the Pacific northwest, and Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* [L.] Karst.) in Sweden and Finland, has been consistent enough that large-scale nitrogen fertilization in these regions is often considered to be an attractive silvicultural investment.

In 1981, the Ministry of Forests initiated a research program to document the responsiveness of lodgepole pine to nitrogen fertilizer application on a range of sites throughout the interior of British Columbia.[1] Because of the excessive density often encountered in unmanaged lodgepole pine, it was decided to limit trial establishment to thinned stands. Increases in foliage mass and photosynthetic capacity are the mechanisms primarily responsible for stimulating tree growth following nitrogen fertilization (Brix and Ebell 1969; Miller and Miller 1976; Fagerstrom and Lohm 1977; Brix 1983). Consequently, the improved light conditions and room for crown expansion present in thinned stands may explain the favourable, often synergistic, growth response obtained from combined fertilizer x thinning treatments with other conifers (Weetman 1975; Jonsson and Möller 1976; University of Wash. 1979; Miller *et al.* 1979; Hall *et al.* 1980). In unthinned stands, growth stimulation due to fertilizer application increases competition and thus accelerates the rate of mortality losses in smaller than average trees, thereby reducing net treatment response.

Initial trial establishment was confined to young (i.e., 15- to 25-year-old) stands. Fertilizing young stands is biologically desirable, because nutrient requirements are high when annual rates of crown expansion and wood production are high (Miller 1981). Stands less than 15 years old were avoided since the gains in wood production resulting from fertilization are largely dependent on the size of the tree. Also, unless stands are free-growing, competing vegetation may use a large portion of the added nutrients, thereby reducing the benefits to crop trees. Older stands, although generally regarded as being economically more attractive because earlier harvest reduces carrying charges on the investment, were excluded from initial trial establishment. At the time the project was initiated, very little stand density control had been undertaken in older lodgepole pine stands throughout the interior of British Columbia. Because the species commonly regenerates overabundantly and is apparently unable to thin itself, many of these older, unmanaged stands

[1] Brockley, R.P. and R. Fahlman. 1981. Responses of thinned immature lodgepole pine to fertilizer application. EP 886.01. B.C. Min. For. Research Branch, Victoria, B.C. Unpubl. working plan.

exhibit poor crown conditions and thus have lower fertilization response potential. However, recent timber supply analyses have indicated that improving the growth of these older, previously unmanaged stands must be a high priority within certain TSA's if timber supply shortfalls are to be avoided. As a result, one EP 886.01 fertilization research installation was established in a 55-year-old lodgepole pine stand in 1986. Other fertilization research projects have also been initiated in older lodgepole pine stands.[2,3]

A total of 15 EP 886.01 installations have been established to date. First-year nutrient concentration and foliage biomass response for 11 of these installations was reported previously (Brockley 1986). This report presents the effects, for the first three growing seasons after treatment, of nitrogen fertilization on the growth of lodgepole pine within these same installations. It is recognized that 3-year results will give only initial treatment response. Future reports, coinciding with a 3-year remeasurement cycle, will provide increasingly more reliable estimates of the total response of thinned lodgepole pine to nitrogen fertilization.

2 METHODS

2.1 Location and Site Description

The sites selected for this study are widely distributed throughout the interior of British Columbia. The 11 installations that are the subject of this report were established between 1981 and 1983 in pure, even-aged, 18- to 25-year-old stands of lodgepole pine that regenerated naturally following wildfire. An additional four installations were established in 1986, but are not part of this report.

Study locations were selected on the basis of homogeneity of site and stand conditions. Vegetation and soils were described by Regional ecology/pedology personnel. Sites were characterized by a thin forest floor, presumably the result of recent (and possibly repeated) fire disturbance. Foliage samples collected at the time of installation establishment indicated severe to very severe nitrogen deficiencies at all study locations. Tables 1 and 2 provide a summary of the installations.

2.2 Study Design and Establishment

Within an installation, three replicates of each of three fertilizer levels (0, 100, and 200 kg N/ha as urea [46-0-0]) were applied to circular treatment plots arranged in a completely randomized design. The size of the plots varied from 0.06 to 0.09 ha depending on the post-thinning stand density prescribed for the site. Three different post-thinning densities were used (1100, 1600, and 2100 stems per hectare); all nine plots within an installation were thinned to the same density. Mensurational data were collected from 0.02- to 0.04-ha subplots in the centre of the treated plots. Each of the subplots contained 50 (±2) sample trees. Consecutively numbered tags were affixed above a painted dbh line on each sample tree. The outer boundaries of adjacent plots were separated by an untreated isolation strip at least 10 m in width. As well, outer edges of plots were located at least 10 m from roads, creeks, and changes in forest type and topography. A typical installation layout is shown in Figure 1.

Installations are of two types: 1) those thinned at the time of fertilization (Type 1); and 2) those operationally thinned a minimum of 2 years prior to fertilization (Type 2). With one exception, both installation types were established adjacent to each other at each study location so that the effects of timing of fertilization in relation to thinning could be evaluated.

Agricultural grade urea (46-0-0) fertilizer was applied by hand to treatment plots in late September to early October. Fall application was chosen to ensure hydrolysis of urea and to minimize volatilization losses during dry springs. Thinning was completed immediately after fertilizer application in Type 1 installations.

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[2] Draper, D. 1987. Response of low-merchantability, repressed lodgepole pine to spacing and fertilization. EP 886.03. B.C. Min. For., Victoria, B.C. Unpubl. progress report.

[3] Yole, D. 1986. Operational fertilization recommendations and single-tree fertilization trials for lodgepole pine in the Prince Rupert Forest Region. B.C. Min. For., Smithers, B.C. Unpubl. contract research report.

TABLE 1. Location, biogeoclimatic classification and stand characteristics of experimental stands

Installation No.	Location	Forest District	Biogeo-climatic Subzone	Ecosystem Association	Elevation (m)	Year thinned	Year estab.	Average age (years)	Average diameter (cm)	Average height (m)	Site[a] index m at 50 years	Pre-spacing density st/ha	Post-spacing density st/ha
1	Lac le Jeune	Kamloops	MSc	04	1420	1978	1981	20	8.3	6.1	20	7000	1100
2	Lac le Jeune	Kamloops	MSc	04	1460	1981	1981	20	6.4	5.7	19	18000	1100
3	Gold Creek	Cranbrook	MSa	04	1450	1979	1982	20	8.2	6.8	20	7500	1100
4	Gold Creek	Cranbrook	MSa	04	1450	1982	1982	20	6.1	6.5	20	18000	1100
5	Frost Lake	Prince George East	SBSjl	06	1000	1982	1982	18	9.3	8.6	23	6000	1100
6	Lord Lake	Lakes	SBSe	04	1130	1980	1982	25	8.0	6.6	16	9000	1600
7	Lord Lake	Lakes	SBSe	04	1130	1982	1982	25	8.6	7.3	17	10000	1600
8	Lintz Lake	Prince George West	SBSk2	03	880	1981	1983	24	6.6	6.9	19	9400	2100
9	Lintz Lake	Prince George West	SBSk2	03	880	1983	1983	24	5.6	6.6	19	19000	2100
10	Tsus Creek	Prince George East	SBSj1	03	820	1979	1983	20	7.9	8.1	21	17000	2100
11	Tsus Creek	Prince George East	SBSj1	03	820	1983	1983	20	6.7	8.3	21	21000	2100

[a] From Goudie, J.W. 1984. Height growth and site index curves for lodgepole pine and white spruce and interim managed stand yield tables for lodgepole pine in British Columbia. B.C. Min. For., Victoria, B.C. Unpubl. contract research report.

TABLE 2. Soil characteristics and initial foliar nutrient concentrations of experimental stands

Installation No.	Location	Parent material	Soil texture	Rooting depth (cm)	pH	Min. N ppm %	Foliar nutrient concentration											
							N %	P %	K %	Ca %	Mg %	S %	B ppm	Cu ppm	Zn ppm	Fe ppm	Active Fe ppm	Mn ppm
1	Lac le Jeune	Glacial till	SiL	30	5.3	38	1.09	.16	.59	.18	.11	.10	25	4	40	29	16	315
2	Lac le Jeune	Glacial till	SL	30	5.5	35	1.17	.15	.53	.17	.12	.10	17	4	42	29	18	207
3	Gold Creek	Glacial till	SiL	40	5.6	25	0.96	.11	.48	.15	.11	.09	17	2	35	37	19	271
4	Gold Creek	Glacial till	SiL	20	5.5	47	0.89	.11	.43	.12	.10	.08	13	2	28	31	19	229
5	Frost Lake	Glacial till	L	20	5.0	11	1.04	.13	.48	.13	.10	.10	12	2	35	34	22	273
6	Lord Lake	Glacial till	L	40	4.8	36	0.95	.12	.44	.15	.09	.08	4	3	33	26	15	444
7	Lord Lake	Glacial till	SL	40	4.7	32	1.02	.12	.42	.15	.10	.09	2	3	37	33	20	416
8	Lintz Lake	Glacial till	SL	15	5.5	27	0.93	.11	.42	.15	.09	.08	17	2	46	25	23	412
9	Lintz Lake	Glacial till	L	15	5.8	13	0.94	.10	.40	.12	.09	.09	10	2	45	22	20	212
10	Tsus Creek	Fluvial	LS	20	4.9	14	1.07	.12	.45	.14	.10	.10	16	2	48	37	27	499
11	Tsus Creek	Fluvial	LS	20	4.7	12	1.01	.12	.39	.14	.10	.09	8	2	42	31	23	553

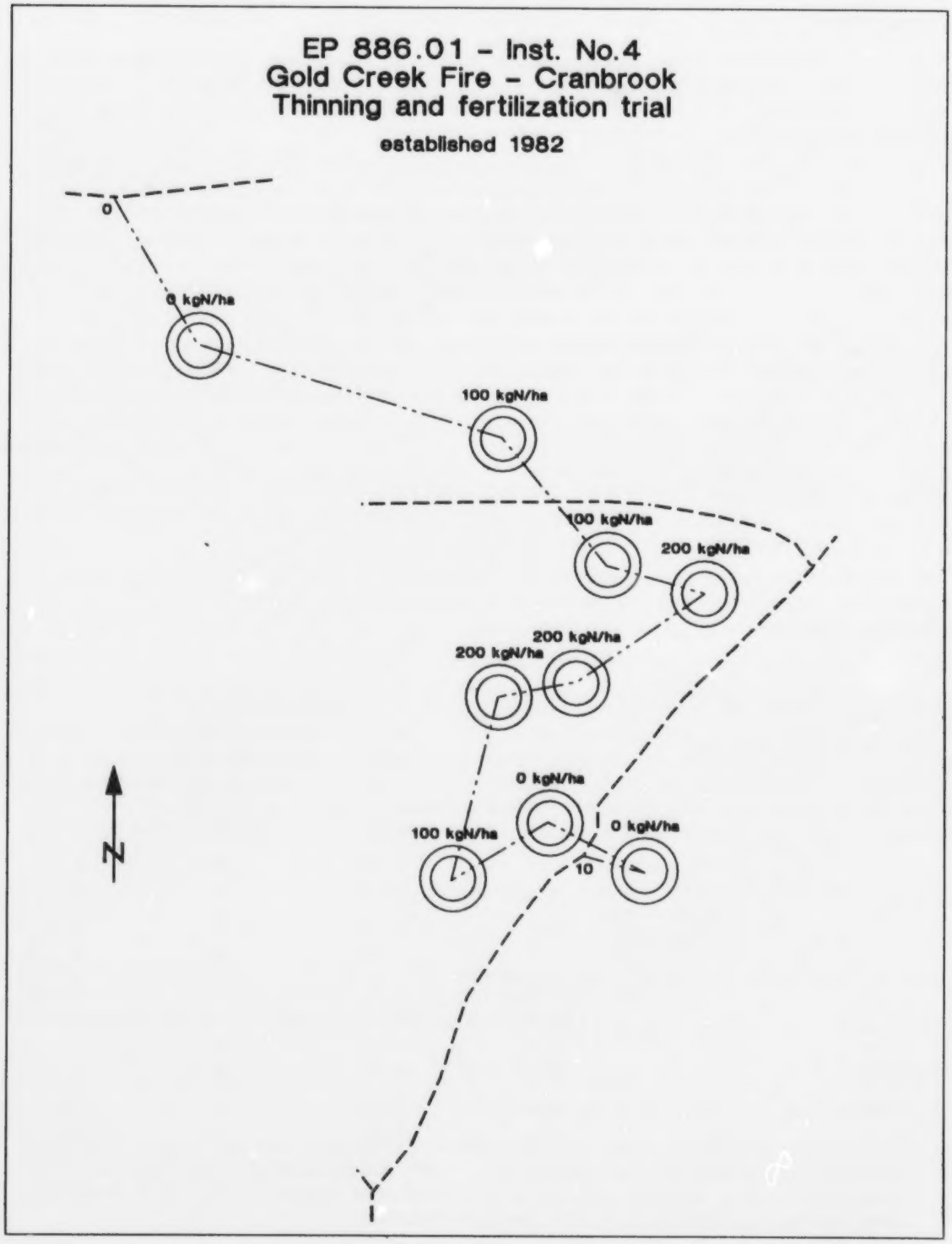


FIGURE 1. Diagram of a typical EP 886.01 installation layout.

2.3 Measurement

At the time of establishment and again 3 years after fertilization, the diameter at breast height (dbhob), total height, height to live crown, and pathological condition of all sample trees were measured and recorded. Diameter and height measurements were made with diameter tapes and telescoping measuring poles, respectively. Breast height measurements were taken at 1.30 m.

Samples of the current year's foliage on the uppermost lateral branches of 10 dominant or co-dominant trees per plot were collected at the time of installation establishment and again after one and three growing seasons. One composite sample per plot, consisting of equal amounts of foliage from each of the 10 trees, was prepared for chemical analysis. Foliar sampling, preparation, and analysis followed procedures outlined by Ballard and Carter (1986). The dry weight of needles (g/100 fascicles) that were produced in the first year after fertilization by each of the 10 sample trees per plot was measured and recorded as a plot total (i.e., g/1000 fascicles).

Soil sampling was undertaken in all installations during July 1986. In each control plot, five locations were randomly selected, and at each location a 15 x 15 x 15 cm mineral soil sample was collected from each of the three apices of a 1-m equilateral triangle. The three samples per sampling location were bulked together to produce five composite samples per plot (15 samples/installation). These samples were air-dried, passed through a 2-mm sieve, and their nitrogen mineralization potential measured using the anaerobic incubation method described by Waring and Bremner (1964). In addition, one composite sample per control plot (comprised of equal amounts of soil from each of the five subsamples) was used for "complete" soil analysis: pH, total N, available ammonium-N, available nitrate-N, organic matter, available P, exchangeable cations, CEC, total S, extractable Zn, Cu, Fe, Mn, B, and particle size distribution.

The amount of red squirrel barking damage was assessed within each plot at the time of installation remeasurement. Damage condition (i.e., damaged vs. undamaged) and maximum percentage of stem circumference girdled was recorded for each sample tree.

To determine initial individual tree and initial plot volumes, a local volume equation was developed for each site, based on sectional measurements made on 36 lodgepole pine trees selected to cover the observed range of dbh. Trees were felled and marked from the base up at 5, 10, 15, and 20% of the total length, and at every 10%-interval thereafter (Kovats 1977). At each section mark, outside bark diameter and two bark thickness measures were taken, using a diameter tape and calipers, respectively. The inside bark section volumes were calculated using Smalian's formula (Chapman and Meyer 1949). A least-squares equation was derived for each installation, using the volume trees and regressing measured volume against dbh and height; the coefficients for these equations are given in Table 3. The general form of these equations is the regression:

$$V = a_1 + a_2 D^2H$$

where V = total volume inside bark in cm^3
D = dbhob in cm
H = total height in m

Changes in tree form resulting from fertilizer treatment were not considered. Consequently, the initial volume equations were applied to all treatment plots to estimate 3-year volume increments. New equations may be derived for future remeasurements if treatment-related differences in bole form can be demonstrated.

2.4 Analysis

Mensurational data were analyzed in two ways:

1. Average response per plot of individual trees, based on those trees alive after 3 years. Response variables (i.e., dbh increment/tree, height increment/tree, volume increment/tree) were subjected to analysis of variance. Diameter and volume increments were adjusted by analysis of covariance, using initial dbh and initial volume, respectively, as covariates.

2. The basal area and volume response of each plot expressed as per-hectare values. Values were calculated in two ways:

i) Net values - i.e., Volume of living trees (year 3) minus Volume of living trees (initial)

ii) Gross values - i.e., (Volume of living trees [year 3] plus initial volume of trees that died during remeasurement period) minus volume of living trees (initial)

Basal area and volume increments were subjected to analysis of covariance using initial basal area per hectare and initial volume per hectare, respectively as covariates.

The primary management objective in fertilization is to speed up the growth of trees that have a high probability of being harvested. Therefore, in addition to analyses using all sample trees, treatment response was calculated for the largest 50% of the sample trees (by dbhob at year 3) and sample trees representing the 580 largest (by dbhob) stems per hectare, irrespective of post-thinning density.

Foliar nutrient concentration, foliage biomass, and squirrel damage data were subjected to one-way analysis of variance. Squirrel damage data (i.e., % mortality, % trees attacked) were transformed by arcsin square root before analysis. Treatment means were compared using Duncan's new multiple range test. In all analyses, the level of significance was at least $p \leq 0.05$.

The effect of partial girdling on volume increment in a given diameter class was analyzed using a t-test for unpaired samples.

Snowpress damage was tabulated by installation type (i.e., Type 1 vs. Type 2) and treatment, and the resulting contingency tables were tested using the chi-square statistic.

TABLE 3. Volume equation coefficients for individual installations. The form of the equation used was $V = a_1 + a_2 D^2 H$

Installation No.	Number of trees	a_1	a_2	R^2	SEE
1	36	238.40	0.47	0.9946	680.75
2	36	238.78	39.67	0.9933	573.56
3	36	1885.26	35.33	0.9878	1294.82
4	36	1254.48	34.86	0.9833	1071.32
5	36	3235.77	32.70	0.9805	2118.79
6	36	1665.77	37.10	0.9769	1625.34
7	36	1850.76	37.07	0.9883	1411.15
8	36	1027.22	35.87	0.9904	1143.34
9	36	279.84	37.91	0.9951	393.60
10	36	1489.35	38.78	0.9923	1035.89
11	36	38.53	40.17	0.9940	597.54

TABLE 4. Diameter - mean annual increments (0-3 years; mm/tree per year) by treatment for individual installations. Numbers in parentheses indicate percentage gains above control. Within each installation, means with different letters are significantly different at $p<0.05$

Installation No.	All trees			Largest 580 stems/ha			Largest 50%		
	0 N	100 N	200 N	0 N	100 N	200 N	0 N	100 N	200 N
1	6.0[a]	7.3[b](22%)	7.8[c](31%)	6.4[a]	8.0[b](23%)	8.4[c](31%)	6.5[a]	8.0[b](23%)	8.5[c](31%)
2	5.1[a]	6.4[b](26%)	6.3[b](23%)	5.6[a]	7.1[b](26%)	7.3[b](29%)	5.7[a]	7.1[b](25%)	7.3[b](28%)
3	5.3[a]	6.6[b](25%)	8.1[c](53%)	5.8[a]	7.1[b](22%)	8.4[c](45%)	5.9[a]	7.1[b](20%)	8.5[c](44%)
4	4.5[a]	6.2[b](39%)	7.0[c](56%)	5.0[a]	6.9[b](39%)	7.4[c](49%)	4.9[a]	7.0[b](43%)	7.4[c](51%)
5	5.4[a]	7.0[b](31%)	7.4[c](39%)	5.9[a]	7.8[b](31%)	8.3[c](40%)	5.9[a]	7.8[b](32%)	8.3[c](41%)
6	3.1[a]	4.4[b](43%)	4.8[c](55%)	3.7[a]	4.8[b](29%)	5.4[c](45%)	3.6[a]	4.8[b](33%)	5.2[c](44%)
7	2.5[a]	3.3[b](35%)	3.2[b](31%)	3.0[a]	3.9[b](27%)	3.8[b](25%)	2.8[a]	3.7[b](32%)	3.7[b](32%)
8	2.9[a]	3.4[b](16%)	3.6[c](23%)	3.5[a]	4.3[b](24%)	4.6[b](31%)	3.3[a]	3.9[b](18%)	4.2[b](27%)
9	3.0[a]	4.4[b](46%)	4.1[c](37%)	3.9[a]	5.3[b](34%)	5.2[b](33%)	3.6[a]	5.0[b](39%)	4.9[b](36%)
10	4.4[a]	5.7[b](27%)	5.4[c](21%)	5.3[a]	6.7[b](27%)	6.4[b](21%)	5.0[a]	6.4[b](28%)	6.0[c](20%)
11	3.3[a]	4.4[b](32%)	4.7[c](43%)	4.1[a]	5.0[b](22%)	5.6[c](36%)	3.7[a]	4.8[b](30%)	5.2[c](41%)
Mean	4.1 ± 1.2*	5.3 ± 1.4 (30%)	5.6 ± 1.7 (37%)	4.7 ± 1.1*	6.0 ± 1.4 (28%)	6.4 ± 1.6 (35%)	4.6 ± 1.3	6.0 ± 1.6 (29%)	6.3 ± 1.8 (36%)

* ± Standard deviation.

RESULTS AND DISCUSSION

3.1 Individual-Tree Response

The 3-year growth (diameter, height, and volume), measured as individual-tree periodic annual increment (PAI; 0-3 years was calculated for each installation and treatment. Basal area is a simple function of diameter and thus is not shown. Treatment means include only those trees alive at the conclusion of the 3-year response period.

Although individual-tree response is ultimately not as useful to the forest manager as land-area increment, these data do indicate the maximum relative response potential of lodgepole pine to nitrogen fertilization on these sites, in the absence of treatment-related mortality and irrespective of post-thinning density.

3.1.1 Diameter

Mean tree dbh (i.e., arithmetic mean) responded signficantly to fertilizer application in all 11 installations (Table 4). Average response for an application of 100 N was 30% (range 16-46%). The corresponding gain from 200 N was 37% (range 21-56%). Trends were similar for the largest 50% and 580 stems per hectare.

Response data indicate a differential response to fertilizer application rate on the various sites. The incremental gains between 100 N and 200 N were statistically significant in seven installations. However, in two installations, the response to 200 N was signficantly less than 100 N.

Quadratic mean diameter (i.e., the diameter at breast height of trees of mean basal area) responded to fertilization in similar manner to the arithmetic mean dbh (Table 5).

TABLE 5. Quadratic mean diameters (dbhob; cm) and increments (PAI: mm/year) by installation and treatment. Numbers in parentheses indicate percentage gains above control

Installation No.	Quadratic mean diameter (cm)						PAI (0-3 years; mm/year)		
	0 N		100 N		200 N		0 N	100 N	200 N
	Initial	3-Year	Initial	3-Year	Initial	3-Year			
1	8.34	10.14	8.50	10.69	8.72	11.00	6.0	7.3 (22%)	7.6 (27%)
2	6.52	8.09	6.21	8.12	6.67	8.61	5.2	6.4 (23%)	6.5 (25%)
3	8.09	9.68	8.59	10.59	8.21	10.61	5.3	6.7 (26%)	8.0 (51%)
4	6.34	7.70	6.29	8.38	6.05	8.50	4.5	7.0 (56%)	8.2 (82%)
5	9.08	10.74	9.64	11.89	9.75	12.16	5.5	7.5 (36%)	8.0 (45%)
6	8.56	9.55	7.90	9.22	7.99	9.43	3.3	4.4 (33%)	4.8 (45%)
7	8.23	8.97	8.66	9.70	9.40	10.46	2.5	3.5 (40%)	3.5 (40%)
8	6.64	7.51	6.64	7.66	7.11	8.25	2.9	3.4 (17%)	3.8 (31%)
9	5.79	6.71	5.50	6.81	5.75	7.04	3.1	4.4 (42%)	4.3 (39%)
10	7.76	9.07	8.18	9.90	8.23	9.88	4.4	5.7 (30%)	5.5 (25%)
11	6.60	7.59	6.79	8.11	7.07	8.53	3.3	4.4 (33%)	4.9 (48%)
						Mean	4.2	5.5 (32%)	5.9 (42%)

3.1.2 Height

Fertilizer application significantly increased 3-year height growth in 5 of the 11 installations (Table 6). Average response for an application rate of 100 N was 22% (range 8-42%). The corresponding gain from 200 N was 19% (range 2-41%). In all cases, differences between 100 N and 200 N were statistically non-significant. Results were similar for the largest 50% and 580 stems per hectare.

The timing of fertilization in relation to thinning had a significant impact on height response to fertilizer applications. For the five locations with paired installations, those that were thinned at the time of fertilization had average height responses of 27% and 24% for application rates of 100 N and 200 N, respectively. Corresponding gains for the adjacent, previously thinned installations were only 16% and 13%. Four out of six stands thinned at the time of fertilization showed a statistically significant height response following nitrogen application, whereas only one out of five previously thinned stands responded significantly. Thinning "shock", or a temporary decline in height growth of crop trees immediately after thinning, has been reported for several tree species (Staebler 1956; Forward and Nolan 1961; Berry 1969; Brix 1981). Data from this study indicate that fertilization may reduce the impact of thinning shock, and are consistent with findings reported by Brix (1981).

3.1.3 Volume

Mean tree volume responded significantly to fertilizer application in all 11 installations (Table 7). Average response for an application of 100 N was 31% (range 18-55%). The corresponding gain for 200 N was 35% (range 15-61%). The absolute gains for the other stand components (i.e., largest 50% and 580 stems per hectare) were larger, but relative responses were slightly smaller.

In three installations an application of 200 N resulted in a statistically significant incremental gain over the growth achieved from 100 N. Conversely, the response to 200 N was significantly less than 100 N in two installations.

Studies elsewhere have shown that trees of different dbh may respond differently to thinning and fertilization (Barclay and Brix 1985). Therefore, a comparison of trees of similar dbh across treatments may be more informative than overall comparisons. Figure 2 compares the volume increment on an individual-tree basis (PAI, 0-3 years), averaged for all installations, across treatments and initial dbh classes. Only those dbh classes common to all treatments were used. Volume increased with increasing initial dbh; however, the growth relative to the original volume is generally greater in the smaller dbh classes.

The timing of fertilization in relation to thinning affected the magnitude and pattern of response to fertilizer application. Whereas absolute volume gains were generally greater in previously thinned installations (primarily attributable to their larger mean dbh), growth relative to unfertilized trees was larger in stands thinned at the time of fertilization (Figure 3). In installations thinned at the time of fertilization, the relative growth response was best in the larger diameter classes (Figure 4). An opposite trend was evident in previously thinned installations (Figure 5).

3.2 Land-Area Response

The 3-year growth on a land-area basis provides measures of actual PAI (0-3 years) for basal area (m^2/ha per year) and volume (m^3/ha per year). Net and gross values were calculated for each installation and treatment.

Land-area response data reflect absolute per-hectare gains attributable to fertilization, and thus are needed by forest managers who must support and rank operational fertilization investments in the interior of British Columbia. Unfortunately, assessment of fertilization effects on stand increment was complicated by substantial treatment-related damage and mortality caused by red squirrel feeding injuries and snowpress during the experimental period. Large reductions in net response occurred in some installations.

TABLE 6. Height - mean annual increments (0-3 years; cm/tree per year) by treatment for individual installations. Numbers in parentheses indicate percentage gains above control. Within each installation, means with different letters are significantly different at $p<0.05$

Installation No.	All trees			Largest 580 stems/ha			Largest 50%		
	0 N	100 N	200 N	0 N	100 N	200 N	0 N	100 N	200 N
1	38.3[a]	43.3[a](14%)	42.0[a](10%)	39.7[a]	45.0[a](13%)	44.3[a](12%)	40.0[a]	45.0[a](12%)	44.3[a](11%)
2	25.0[a]	28.7[a](15%)	29.0[a](16%)	28.3[a]	32.0[a](13%)	31.0[a](10%)	28.0[a]	32.3[a](15%)	31.3[a](12%)
3	33.0[a]	40.7[b](23%)	41.7[b](26%)	36.0[a]	41.3[b](15%)	43.7[b](21%)	36.0[a]	41.0[b](14%)	43.3[b](20%)
4	19.3[a]	27.7[b](42%)	26.7[b](38%)	21.7[a]	29.7[b](37%)	28.0[ab](29%)	21.7[a]	29.7[b](37%)	28.0[ab](29%)
5	27.0[a]	37.3[b](39%)	36.7[b](36%)	30.0[a]	40.0[b](33%)	38.7[b](29%)	30.3[a]	40.0[b](32%)	39.0[b](29%)
6	20.7[a]	22.7[a](11%)	21.0[a](2%)	25.0[a]	25.7[a](3%)	24.0[a](-4%)	23.7[a]	25.3[a](7%)	23.3[a](-2%)
7	13.0[a]	14.0[a](8%)	12.7[a](-2%)	15.7[a]	16.0[a](2%)	13.0[a](-17%)	15.3[a]	15.7[a](3%)	13.3[a](-13%)
8	21.7[a]	25.7[a](18%)	25.7[a](18%)	25.3[a]	30.3[a](20%)	30.0[a](19%)	24.0[a]	28.0[a](17%)	28.3[a](18%)
9	16.7[a]	22.3[b](34%)	20.7[ab](24%)	20.3[a]	28.0[b](38%)	26.0[ab](28%)	19.0[a]	25.3[b](33%)	23.7[ab](25%)
10	39.7[a]	45.0[a](13%)	42.7[a](8%)	44.3[a]	48.7[a](10%)	43.7[a](-1%)	44.0[a]	48.0[a](9%)	43.6[a](-1%)
11	18.0[a]	24.0[b](33%)	25.3[b](41%)	21.7[a]	29.3[b](35%)	28.7[b](32%)	20.6[a]	27.0[b](31%)	27.3[b](32%)
Mean	24.8 ± 8.9*	30.2 ± 10.0 (22%)	29.5 ± 10.0 (19%)	28.0 ± 8.8	33.3 ± 9.5 (19%)	31.9 ± 9.8 (14%)	27.5 ± 9.1	32.5 ± 9.8 (18%)	31.4 ± 10.0 (14%)

* ± Standard deviation.

TABLE 7. Volume - mean annual increments (0-3 years; cm^3/tree per year) by treatment for individual installations. Numbers in parentheses indicate percentage gains above control. Within each installation, means with different letters are significantly different at $p<0.05$

Installation No.	All trees			Largest 580 stems/ha			Largest 50%		
	0 N	100 N	200 N	0 N	100 N	200 N	0 N	100 N	200 N
1	4251[a]	5253[b](24%)	5468[b](29%)	5466[a]	6786[b](24%)	7066[b](29%)	5539[a]	6884[b](24%)	7140[b](29%)
2	2366[a]	3110[b](31%)	3021[b](28%)	3056[a]	3953[b](29%)	4045[b](32%)	3093[a]	3996[b](29%)	4092[b](32%)
3	3600[a]	4507[b](25%)	5423[c](51%)	4592[a]	5591[b](22%)	6634[c](45%)	4651[a]	5598[b](20%)	6683[c](44%)
4	1952[a]	2851[b](46%)	3142[c](61%)	2388[a]	3565[b](49%)	3765[b](58%)	2397[a]	3617[b](51%)	3800[b](59%)
5	4524[a]	6071[b](34%)	6315[b](40%)	5680[a]	7649[b](35%)	8024[b](41%)	5741[a]	7727[b](35%)	8104[b](41%)
6	1993[a]	2794[b](40%)	2910[b](46%)	3094[a]	3924[b](27%)	4183[b](35%)	2779[a]	3652[b](31%)	3836[b](38%)
7	1792[a]	2275[b](27%)	2144[b](20%)	2735[a]	3221[b](18%)	2927[ab](7%)	2459[a]	2961[b](20%)	2738[b](11%)
8	1632[a]	1920[b](18%)	2001[b](23%)	2664[a]	3275[b](23%)	3432[b](29%)	2264[a]	2700[b](19%)	2814[b](24%)
9	1240[a]	1916[b](55%)	1800[c](45%)	2222[a]	3114[b](40%)	3118[b](40%)	1789[a]	2618[b](46%)	2550[b](43%)
10	4039[a]	5017[b](24%)	4660[c](15%)	6174[a]	7722[b](25%)	7062[c](14%)	5393[a]	6719[b](25%)	6127[c](14%)
11	2199[a]	2910[b](32%)	3146[c](43%)	3380[a]	4258[b](26%)	4654[c](38%)	2856[a]	3735[b](31%)	4010[c](40%)
Mean	2690 ± 1177*	3511 ± 1446 (31%)	3639 ± 1563 (35%)	3768 ± 1439	4823 ± 1794 (28%)	4992 ± 1840 (32%)	3542 ± 1481	4564 ± 1835 (29%)	4718 ± 1948 (33%)

* ± Standard deviation.

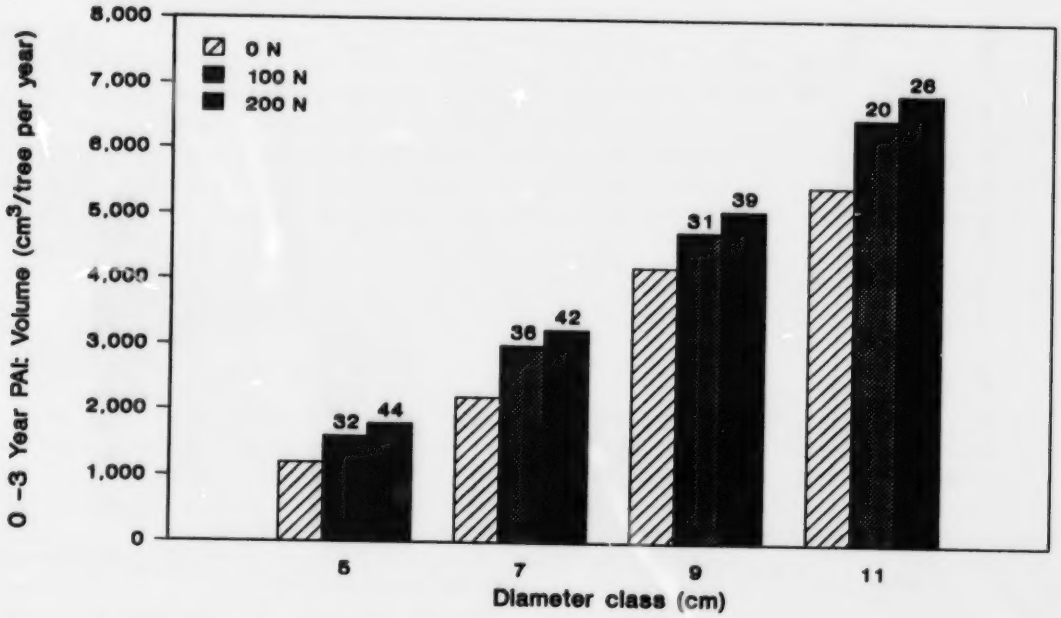


FIGURE 2. The effect of fertilization on periodic annual volume growth (0-3 years) graphed by diameter class; individual-tree analysis (cm^3/tree per year).

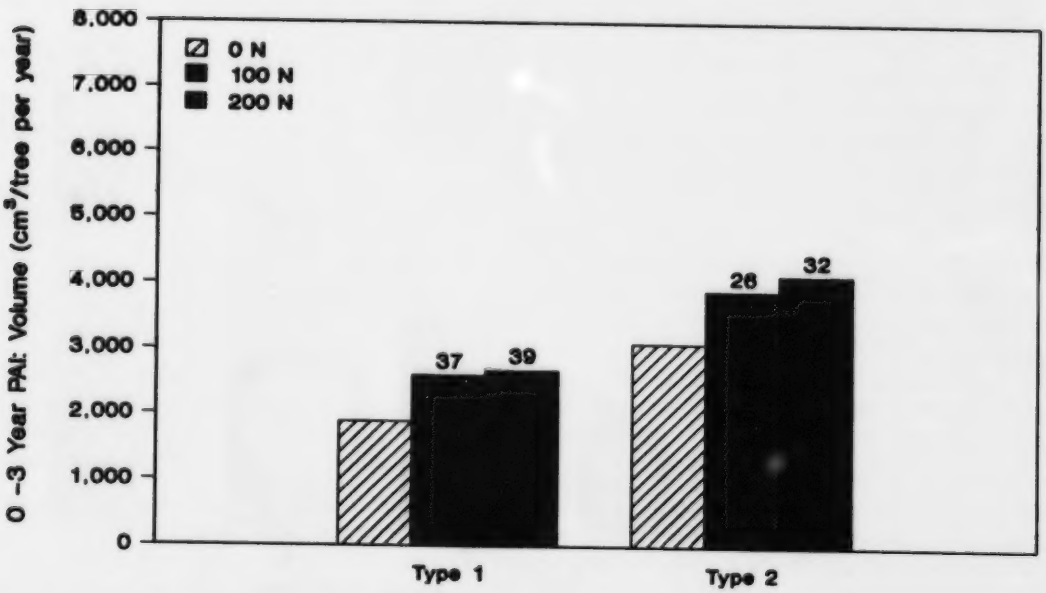


FIGURE 3. The effect of fertilization on periodic annual volume growth (0-3 years) of installations thinned at the time of fertilization (Type 1) and those thinned 2-3 years prior to fertilization (Type 2); individual-tree analysis (cm^3/tree per year).

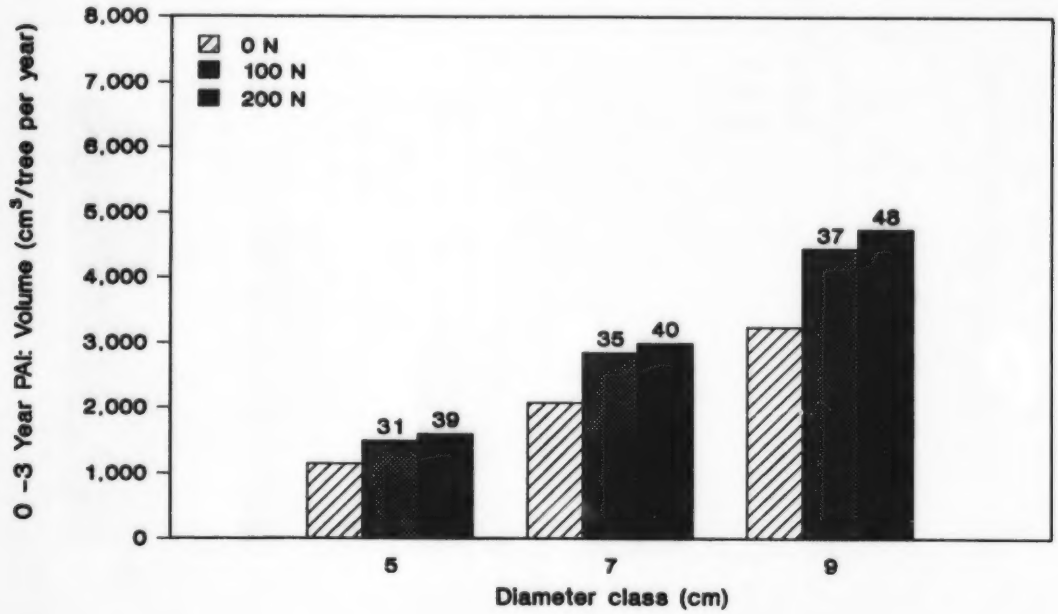


FIGURE 4. The effect of fertilization on periodic annual volume growth (0-3 years) of installations thinned at the time of fertilization (Type 1) graphed by diameter class; individual-tree analysis (cm^3/tree per year).

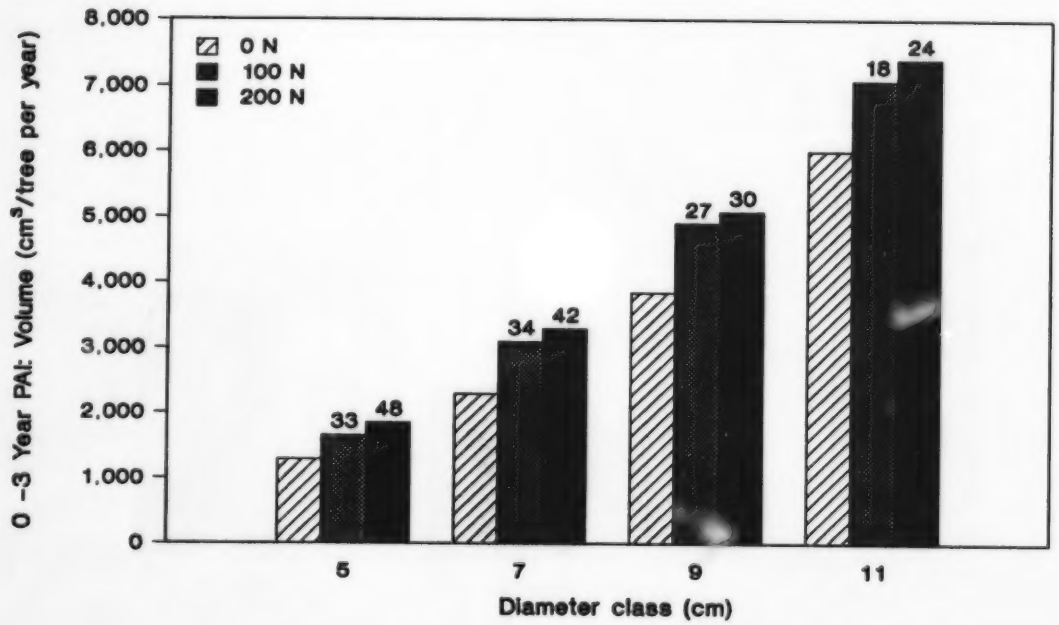


FIGURE 5. The effect of fertilization on periodic annual volume growth (0-3 years) of installations thinned 2-3 years prior to fertilization (Type 2) graphed by diameter class; individual-tree analysis (cm^3/tree per year).

3.2.1 Basal area

The 3-year gross and net basal area increments are shown in Table 8. Fertilization significantly increased gross basal area increment in 8 of the 11 installations. Average gross response (i.e., growth exceeding control) for applications of 100 and 200 N were 0.25 m^2/ha per year (32%) and 0.30 m^2/ha per year (39%), respectively. The incremental gain between 100 and 200 N was statistically significant in only one installation. Trends were similar for the largest 50% and 580 stems per hectare (Table 9).

Because of the large amount of treatment-related damage and mortality, net basal area response was statistically significant in only 5 of the 11 installations. In three installations (Nos. 2, 4 and 5), these losses all but wiped out the positive effects of fertilizer application.

3.2.2 Volume

The 3-year gross and net volume increments are shown in Table10. Fertilization significantly increased gross volume increment in 8 of the 11 installations. Gross PAI exceeding control averaged 1.19 (range 0.59-2.01) m^3/ha per year and 1.32 (range 0.42-2.18) m^3/ha per year for application rates of 100 and 200N, respectively. In relative terms, these responses averaged 31% (range 19-62%) and 34% (range 18-50%). Trends were similar for the largest 50% and 580 stems per hectare (Table 11). As with basal area increment, the incremental gain between 100 and 200 N was statistically significant in only one installation.

Net volume response to nitrogen fertilization was statistically significant in 6 of the 11 installations. As with net basal area response, the positive effects of nitrogen on stand growth were largely negated by treatment-related damage and mortality in some installations. Losses were greatest in stands thinned at the time of fertilization.

The timing of fertilization in relation to thinning affected the magnitude and pattern of volume response. For the five study locations with both types of installations, absolute volume gains were generally greater in previously thinned installations (primarily because of their larger initial dbh), whereas growth relative to control plots was larger in stands thinned at the time of fertilization (Figure 6).

3.3 Foliage Biomass Response and the Foliar Graphical Diagnostic Technique

To evaluate the effectiveness of various fertilizer treatments, a quick and reliable method for assessing fertilization response potential is desirable rather than waiting for long-term quantitative measures of volume growth increment. The foliar graphical diagnostic technique has proven to be a useful method of obtaining an early indication of growth response potential to fertilizer application (Timmer and Stone 1978; Weetman and Fournier 1982; Timmer and Morrow 1984).

The method involves simultaneous comparison of foliage dry weight, nutrient concentration, and nutrient content by combining them in a single display (Figure 7). Inferences about nutrient uptake, growth dilution, luxury consumption, and possible induced deficiencies can be made by examining the amount and direction of change between the plotted points representing the control and treatments. The system has been modified by Morrow (1979) and Weetman and Fournier (1986) to allow comparisons between different stands instead of different treatments within one stand. To compensate for between-stand differences in nutrient levels and dry weight of needles, and thus insure that comparisons are made on a common base, only relative responses amongst individual stands are assessed (i.e., ratio of treated:control values).

Figure 8 indicates the relative responsiveness of the 11 installations to an application of 200 kg N/ha. The relative responses in needle nutrient concentration and nutrient content are represented on the y- and x-axis, respectively. The origin depicts the common base (i.e., the initial status of each stand) and the diagonal lines from the origin are lines of equal needle weight response. Thus, the magnitude of the angular shift from the y-axis provides a measure of the relative response potential of the various installations to fertilizer application. As illustrated in Figure 8, the foliar graphical diagnostic technique was generally successful in identifying the most responsive stands (based on 3-year volume response data).

TABLE 8. Basal area (all trees) - mean annual increments (0-3 years; m²/ha per year) by treatment for individual installations. Numbers in parentheses indicate percentage gains above control. Within each installation, means with different letters are significantly different at $p<0.05$

Installation No.	Gross increment			Net increment		
	0 N	100 N	200 N	0 N	100 N	200 N
1	0.95[a]	1.22[b](28%)	1.27[b](34%)	0.92[a]	1.22[b](32%)	1.22[b](32%)
2	0.66[a]	0.86[b](31%)	0.76[ab](16%)	0.64[a]	0.82[a](29%)	0.63[a](-2%)
3	0.86[a]	1.09[b](28%)	1.34[c](56%)	0.86[a]	1.09[b](28%)	1.34[c](56%)
4	0.53[a]	0.68[a](28%)	0.73[a](39%)	0.51[a]	0.53[a](4%)	0.51[a](0%)
5	0.96[a]	1.21[a](26%)	1.29[a](34%)	0.94[a]	1.01[a](7%)	1.05[a](12%)
6	0.68[a]	0.99[b](45%)	1.07[b](57%)	0.66[a]	0.98[b](48%)	1.04[b](57%)
7	0.52[a]	0.76[b](46%)	0.80[b](54%)	0.43[a]	0.68[b](58%)	0.75[b](73%)
8	0.67[a]	0.80[a](20%)	0.87[a](31%)	0.63[a]	0.80[a](26%)	0.86[a](36%)
9	0.60[a]	0.91[b](52%)	0.86[ab](43%)	0.58[a]	0.88[a](53%)	0.85[a](47%)
10	1.25[a]	1.65[b](32%)	1.61[b](28%)	1.24[a]	1.60[a](28%)	1.61[a](30%)
11	0.77[a]	1.05[b](37%)	1.17[b](52%)	0.75[a]	1.05[b](40%)	1.16[b](54%)
Mean	0.77 ± 0.22*	1.02 ± 0.27 (32%)	1.07 ± 0.29 (39%)	0.74 ± 0.23	0.97 ± 0.29 (31%)	1.00 ± 0.32 (35%)

* ± Standard deviation.

TABLE 9. Basal area (largest component) - mean annual increments (0-3 years; m²/ha per year) by treatment for individual installations. Numbers in parentheses indicate percentage gains above control. Within each installation, means with different letters are significantly different at $p<0.05$

Installation No.	Largest 580 stems/ha			Largest 50%		
	0 N	100 N	200 N	0 N	100 N	200 N
1	0.62[a]	0.78[b](27%)	0.84[b](36%)	0.60[a]	0.76[b](27%)	0.81[b](36%)
2	0.40[a]	0.55[b](36%)	0.54[b](35%)	0.39[a]	0.53[b](35%)	0.53[b](35%)
3	0.54[a]	0.65[b](21%)	0.80[c](48%)	0.52[a]	0.63[b](20%)	0.77[c](48%)
4	0.34[a]	0.50[ab](47%)	0.54[b](59%)	0.33[a]	0.49[a](48%)	0.52[a](55%)
5	0.63[a]	0.83[b](32%)	0.89[b](40%)	0.61[a]	0.81[b](32%)	0.86[b](40%)
6	0.33[a]	0.46[b](39%)	0.52[c](55%)	0.43[a]	0.61[b](41%)	0.67[c](54%)
7	0.30[a]	0.38[b](28%)	0.38[ab](28%)	0.36[a]	0.49[b](36%)	0.51[ab](41%)
8	0.29[a]	0.36[ab](24%)	0.38[b](34%)	0.45[a]	0.54[ab](20%)	0.59[b](29%)
9	0.27[a]	0.39[a](43%)	0.37[a](37%)	0.41[a]	0.60[b](47%)	0.57[b](40%)
10	0.51[a]	0.66[b](29%)	0.62[ab](21%)	0.81[a]	1.06[b](32%)	0.99[ab](23%)
11	0.33[a]	0.40[b](22%)	0.45[b](35%)	0.51[a]	0.66[b](30%)	0.71[b](40%)
Mean	0.41 ± 0.14*	0.54 ± 0.17 (32%)	0.58 ± 0.19 (41%)	0.49 ± 0.14	0.65 ± 0.17 (33%)	0.68 ± 0.16 (39%)

* ± Standard deviation.

TABLE 10. Volume (all trees) - mean annual increments (0-3 years; m^3/ha per year) by treatment for individual installations. Numbers in parentheses indicate percentage gains above control. Within each installation, means with different letters are significantly different at $p<0.05$

Installation No.	Gross Increment			Net Increment		
	0 N	100 N	200 N	0 N	100 N	200 N
1	4.61[a]	5.80[b](26%)	5.86[b](27%)	4.53[a]	5.80[b](28%)	5.68[b](25%)
2	2.68[a]	3.45[b](29%)	3.10[ab](16%)	2.61[a]	3.33[a](28%)	2.66[a](2%)
3	4.05[a]	5.07[b](25%)	6.08[c](50%)	4.05[a]	5.07[b](25%)	6.08[c](50%)
4	2.04[a]	2.63[a](29%)	2.80[a](38%)	2.02[a]	2.10[a](4%)	2.01[a](0%)
5	4.68[a]	6.19[a](32%)	6.56[a](40%)	4.38[a]	5.42[a](24%)	5.75[a](31%)
6	3.17[a]	4.53[b](43%)	4.66[b](47%)	3.07[a]	4.54[b](48%)	4.56[b](48%)
7	2.51[a]	3.50[b](39%)	3.65[b](45%)	2.16[a]	3.18[b](47%)	3.46[b](60%)
8	3.31[a]	3.93[a](19%)	4.03[a](22%)	3.21[a]	3.93[a](23%)	3.99[a](24%)
9	2.48[a]	4.01[b](62%)	3.70[b](49%)	2.37[a]	3.93[ab](65%)	3.66[b](54%)
10	8.30[a]	10.31[b](24%)	9.80[ab](18%)	8.26[a]	10.06[a](22%)	9.84[a](19%)
11	4.37[a]	5.94[b](36%)	6.55[b](50%)	4.29[a]	5.93[b](38%)	6.52[b](52%)
Mean	3.84 ± 1.74*	5.03 ± 2.09 (31%)	5.16 ± 2.06 (34%)	3.72 ± 1.77	4.84 ± 2.10 (30%)	4.93 ± 2.18 (33%)

* ± Standard deviation.

TABLE 11. Volume (largest component) - mean annual increments (0-3 years; m^3/ha per year) by treatment for individual installations. Numbers in parentheses indicate percentage gains above control. Within each installation, means with different letters are significantly different at $p<0.05$

Installation No.	Largest 580 stems/ha			Largest 50%		
	0 N	100 N	200 N	0 N	100 N	200 N
1	3.17[a]	3.92[b](24%)	4.08[b](29%)	3.09[a]	3.82[b](24%)	3.96[b](28%)
2	1.72[a]	2.37[b](38%)	2.30[b](34%)	1.67[a]	2.30[b](37%)	2.24[b](34%)
3	2.68[a]	3.20[b](19%)	3.84[c](43%)	2.61[a]	3.08[b](18%)	3.72[c](43%)
4	1.35[a]	2.01[b](49%)	2.21[b](64%)	1.32[a]	1.99[b](51%)	2.11[b](60%)
5	3.33[a]	4.42[b](33%)	4.59[b](38%)	3.25[a]	4.29[b](32%)	4.45[b](37%)
6	1.75[a]	2.31[b](32%)	2.45[b](40%)	2.19[a]	2.98[b](36%)	3.11[b](42%)
7	1.51[a]	1.86[b](23%)	1.78[ab](19%)	1.85[a]	2.37[b](28%)	2.36[ab](27%)
8	1.56[a]	1.94[b](25%)	1.97[b](27%)	2.37[a]	2.84[a](20%)	2.89[a](22%)
9	1.23[a]	1.93[b](56%)	1.77[ab](44%)	1.79[a]	2.82[b](57%)	2.63[b](47%)
10	3.65[a]	4.47[b](22%)	4.11[ab](13%)	5.65[a]	6.98[b](23%)	6.37[ab](13%)
11	1.98[a]	2.49[b](26%)	2.70[b](37%)	2.98[a]	3.89[b](31%)	4.17[b](40%)
Mean	2.18 ± 0.87*	2.81 ± 1.02 (29%)	2.89 ± 1.05 (33%)	2.62 ± 1.19	3.40 ± 1.39 (30%)	3.46 ± 1.26 (32%)

* ± Standard deviation.

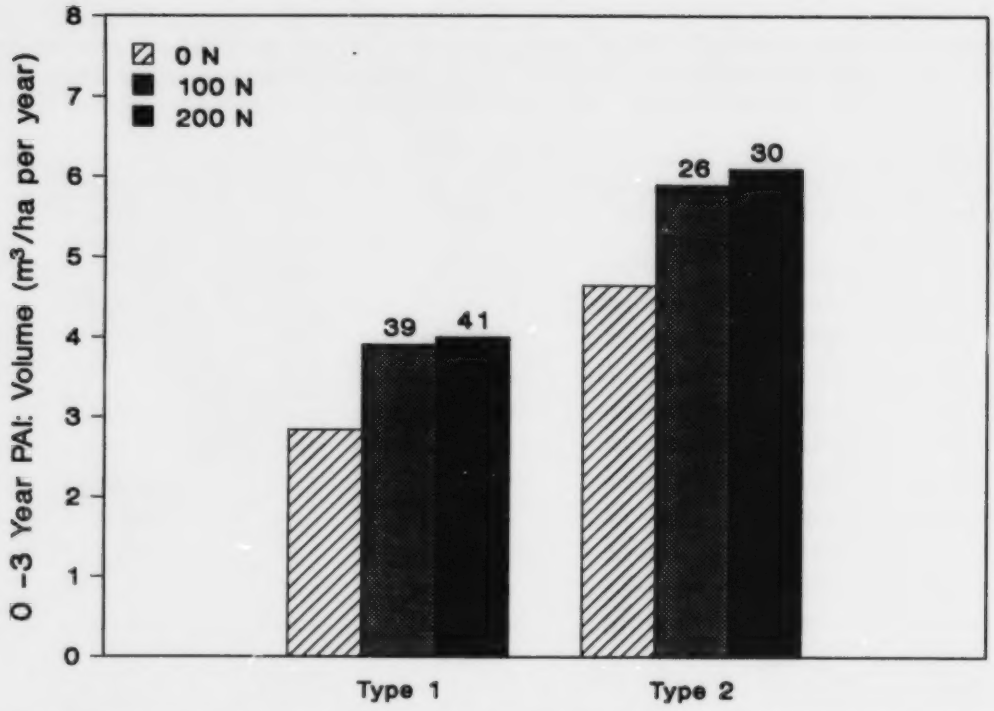
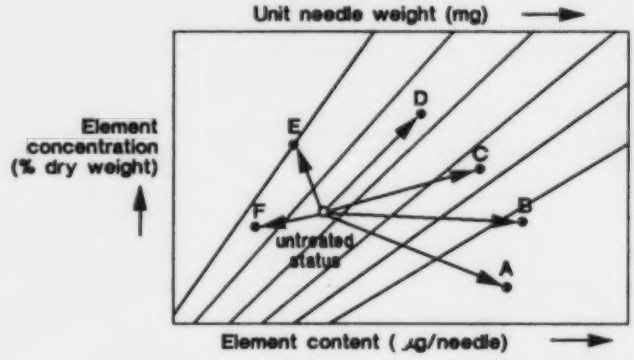


FIGURE 6. The effect of fertilization on periodic annual gross volume growth (0-3 years; all trees) of installations fertilized at the time of thinning (Type 1) and those thinned 2-3 years prior to fertilization (Type 2); land-area analysis (m³/ha per year).



Direction of shift	Response in Needle weight	Response in Nutrient Conc.	Response in Nutrient Content	Nutrient status	Possible diagnosis
A	+	–	+	Dilution	Non-limiting
B	+	0	+	Unchanged	Non-limiting
C	+	+	+	Deficiency	Limiting
D	0	+	+	Luxury consumption	Non-toxic
E	–	++	±	Excess	Toxic
F	–	–	–	Excess	Antagonistic

FIGURE 7. Interpretation of directional relationships between foliar concentration, nutrient content and dry weight of needles following fertilization (after Timmer and Stone 1978).

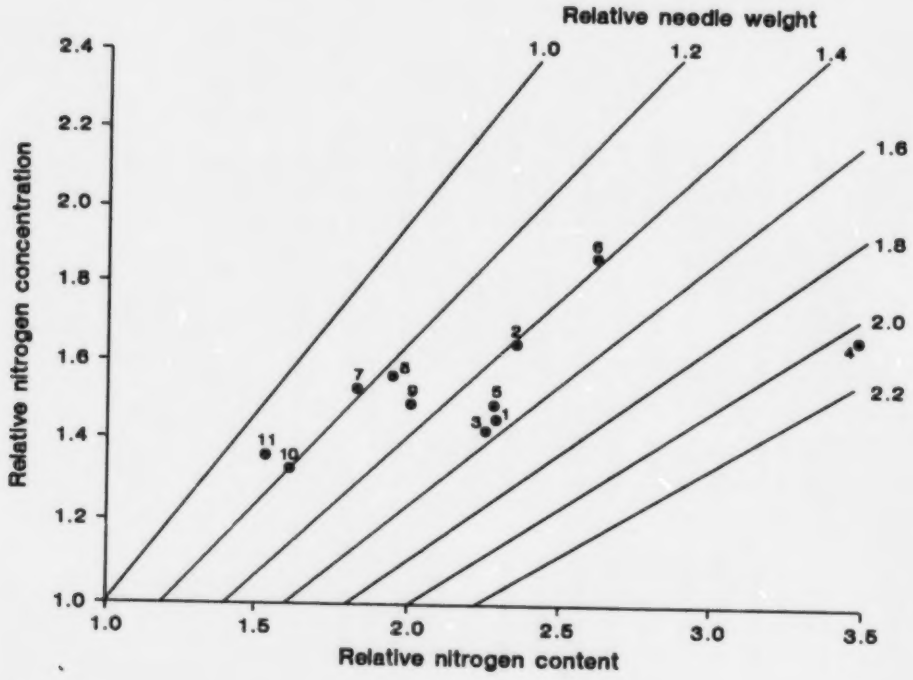


FIGURE 8. Relative responsiveness of EP 886.01 installations to an application of 200 kg N/ha.

These results agree with those reported by Weetman *et al.* (1988), who found that graphical diagnosis of shifts in needle weight and foliar nutrient concentrations and contents in the first growing season following fertilization generally corresponded with subsequent 4-year basal area response in lodgepole pine fertilizer screening trials. In all installations, the needles formed in the year after nitrogen application were significantly heavier and had higher nitrogen concentrations, and thus increased nitrogen uptake (Tables 12 and 13). This is a "C" shift (Figure 7) indicating that the initial foliar nitrogen concentrations were limiting. In fact, a significant ($p<0.01$) positive correlation ($r=0.61$) was obtained between 1st-year needle weight response (relative to the control = 100) and relative 3-year tree volume response. Similar relationships have been demonstrated for jack pine and other conifers (Weetman and Algar 1974; Camire and Bernier 1981; Timmer and Morrow 1984). Only for installation No. 11 did the foliar graphical diagnostic technique seriously underestimate subsequent volume response. However, increment core data from that installation also indicated a 1-year delay in bole increment, which may have been due to a large initial response of unfertilized trees to thinning. Conversely, the technique overestimated subsequent tree volume response for installations 1 and 2, probably due to the severe red squirrel barking injuries inflicted on fertilized crop trees soon after fertilizer application.

Despite the large initial increase in foliage biomass and foliar nitrogen concentration in fertilized plots, foliar % N and needle weights in the 100 N plots were generally not significantly different than control plots after 3 years (Tables 12 and 13). In many installations, however, % N and unit needle weight in 200 N plots remained significantly higher than in unfertilized plots. Studies with other conifer species have shown that, in addition to its positive effect on needle size, nitrogen fertilization (especially when combined with thinning) may also promote increases in number of needles, needle retention, and photosynthetic efficiency (Miller and Miller 1976; Brix 1981; Brix 1983), with beneficial effects on the magnitude and duration of growth response. For Douglas-fir, Brix (1981) reported that maximum foliage mass per tree was not reached until 4-7 years after fertilization. Assuming that these findings also apply to lodgepole pine, the prospects for prolonged growth response to combined thinning and fertilization in these installations appear favourable.

TABLE 12. Mean foliage biomass (g/1000 fascicles) by treatment for individual installations. Numbers in parentheses indicate percentage gains above control. Within each installation, means with different letters are significantly different at $p<0.05$

Installation No.	Initial			1st year			3rd year		
	0 N	100 N	200 N	0 N	100 N	200 N	0 N	100 N	200 N
1	41.47^{a}	44.30^{a}	49.37^{a}	44.66^{a}	63.26^{b}(42%)	69.27^{b}(55%)	42.83^{a}	44.39^{a}(4%)	47.07^{a}(10%)
2	43.11^{a}	42.99^{a}	41.41^{a}	40.85^{a}	53.65^{b}(31%)	57.70^{b}(41%)	49.76^{a}	50.30^{ab}(1%)	53.46^{b}(7%)
3	43.38^{a}	41.81^{a}	43.43^{a}	45.49^{a}	59.69^{b}(31%)	71.83^{c}(58%)	37.67^{a}	33.73^{a}(-10%)	40.19^{a}(7%)
4	34.19^{a}	34.24^{a}	36.33^{a}	30.76^{a}	50.83^{b}(65%)	64.50^{c}(110%)	37.97^{a}	44.58^{b}(17%)	47.72^{b}(26%)
5	38.40^{a}	44.17^{b}	39.55^{a}	33.46^{a}	50.46^{b}(51%)	50.65^{b}(51%)	49.42^{a}	50.64^{a}(2%)	50.07^{a}(1%)
6	37.46^{b}	34.91^{a}	37.81^{b}	30.11^{a}	43.10^{b}(43%)	41.82^{b}(39%)	39.23^{a}	40.55^{a}(3%)	46.34^{b}(18%)
7	37.50^{a}	36.83^{a}	40.03^{a}	28.78^{a}	31.92^{ab}(11%)	34.06^{b}(18%)	41.29^{a}	44.23^{ab}(7%)	49.61^{b}(20%)
8	28.73^{a}	29.77^{a}	28.14^{a}	39.48^{a}	47.69^{b}(21%)	48.59^{b}(23%)	35.27^{a}	40.42^{a}(15%)	41.21^{a}(17%)
9	28.43^{a}	29.94^{a}	30.74^{a}	41.78^{a}	52.49^{b}(26%)	55.05^{b}(32%)	46.59^{a}	45.54^{a}(-2%)	46.07^{a}(-1%)
10	41.56^{a}	40.63^{a}	42.08^{a}	51.49^{a}	59.51^{ab}(16%)	61.02^{b}(19%)	41.36^{a}	45.15^{a}(9%)	52.99^{b}(28%)
11	33.79^{a}	34.91^{a}	33.68^{a}	41.62^{a}	46.58^{b}(17%)	46.79^{ab}(12%)	38.84^{a}	42.61^{a}(10%)	49.79^{b}(28%)
Mean	37.09 ± 5.30	37.68 ± 5.39	38.42 ± 6.03	38.95 ± 7.28	51.02 ± 8.67 (31%)	54.66 ± 11.66 (33%)	41.84 ± 4.85	43.83 ± 4.69 (5%)	47.68 ± 4.22 (14%)

TABLE 13. Foliar nitrogen concentration (%) by treatment for individual installations. Within each installation, means with different letters are significantly different at $p<0.05$

Installation No.	Initial			1st year			3rd year		
	0 N	100 N	200 N	0 N	100 N	200 N	0 N	100 N	200 N
1	1.09[a]	1.10[a]	1.16[a]	1.05[a]	1.23[b]	1.54[c]	1.08[a]	1.09[a]	1.16[a]
2	1.17[a]	1.18[a]	1.21[a]	1.03[a]	1.33[b]	1.71[c]	0.98[a]	1.00[a]	1.04[a]
3	0.96[a]	0.95[a]	0.98[a]	1.06[a]	1.12[a]	1.52[b]	0.94[a]	0.87[a]	0.96[a]
4	0.89[a]	0.90[a]	0.89[a]	1.06[a]	1.36[b]	1.75[c]	1.04[a]	1.04[a]	1.13[a]
5	1.04[a]	1.07[a]	1.09[a]	1.03[a]	1.29[b]	1.54[c]	1.08[a]	1.09[a]	1.23[b]
6	0.95[a]	0.91[a]	0.94[a]	0.86[a]	1.16[b]	1.62[c]	0.98[a]	1.01[ab]	1.13[b]
7	1.02[a]	1.02[a]	1.04[a]	0.93[a]	1.20[b]	1.43[c]	1.01[a]	1.10[a]	1.26[b]
8	0.93[a]	0.95[a]	0.98[a]	1.03[a]	1.46[b]	1.62[b]	1.04[a]	1.21[b]	1.36[c]
9	0.94[a]	0.92[a]	0.93[a]	1.11[a]	1.50[b]	1.68[b]	1.01[a]	1.06[a]	1.28[b]
10	1.07[a]	1.10[a]	1.09[a]	1.22[a]	1.34[b]	1.63[c]	1.03[a]	1.01[a]	1.13[b]
11	1.01[a]	1.07[a]	1.03[a]	1.04[a]	1.30[b]	1.43[b]	1.00[a]	1.07[a]	1.24[b]
Mean	1.01 ± 0.08	1.02 ± 0.09	1.03 ± 0.10	1.04 ± 0.09	1.30 ± 0.12	1.59 ± 0.11	1.02 ± 0.04	1.05 ± 0.08	1.17 ± 0.11

3.4 Mineralizable Nitrogen

A number of studies have found an inverse relationship between the amount of nitrogen mineralized during incubation of mineral soil samples collected from a site, and response to nitrogen fertilization (Shumway and Atkinson 1978; Powers 1980, 1983; Radwan and Shumway 1984). These results indicate that mineralizable nitrogen may be a promising method of predicting the response potential of trees to nitrogen fertilization, provided that other factors are not limiting.

In this study, no relationship could be established between mineralizable nitrogen and 3-year relative tree volume response. These data indicate that factors in addition to nitrogen may limit the growth of lodgepole pine in interior forests.

3.5 Factors Limiting the Response to Nitrogen Fertilization

3.5.1 Other possible nutrient deficiencies

Initial foliar nitrogen concentration data agree with those reported by Ballard (1982), who concluded that severe to very severe nitrogen deficiencies are common throughout the interior of British Columbia. Fire-origin lodgepole pine stands may be especially susceptible to deficiencies due to nitrogen volatilization losses in fires. Young, fire-origin stands generally have thin forest floors and little incorporation of organic matter in the surface mineral soil. However, % foliar nitrogen was low in all installations, and thus no relationship between initial foliar % N and subsequent growth response to nitrogen fertilization could be established. These results, combined with the poor relationship between mineralizable nitrogen and 3-year volume response, indicate that nitrogen status alone is clearly not a reliable predictor of the potential responsiveness of lodgepole pine to nitrogen fertilization. In some installations, large increases in foliar % N in the absence of large responses in needle dry weight or subsequent volume increment indicated the presence of other growth-limiting factors. Although other stand and site factors may be involved, foliar nutrient concentration data and the foliar graphical diagnostic technique indicate that boron and/or sulphur deficiency, either induced or aggravated by nitrogen fertilization, may partially explain why some installations are more responsive than others.

Foliar boron concentration declined with increasing nitrogen application rate in all installations. As illustrated in Figure 9, the decline was probably of greatest significance for study locations in the north-central Interior, since initial foliar boron concentrations were generally lower in these installations. One year following an application of 200 N, average foliar boron concentrations for these installations were at, or near, the boron deficiency level (10 ppm) suggested by Ballard and Carter (1986). Although this was largely a "dilution" effect, there was evidence of reduced boron uptake at the 200 N application rate in five installations. Similar antagonism was indicated by Wikner (1983) following nitrogen fertilization in Sweden.

In installation No. 7, nitrogen fertilization almost certainly induced or aggravated a boron deficiency. Average initial foliar boron concentration of unfertilized trees was 2 ppm, suggested as being a severely deficient level for other species (Lambert and Turner 1977; Aronnson 1983; Braekke 1983*b*). The form and vigour of trees within this installation are generally poor, the most prominent growth disturbance symptoms being die-back and discoloration of the leader and multi-leadered, bushy crowns (Figure 10). Visual growth disturbances were aggravated by nitrogen fertilization and agreed well with boron deficiency symptoms described by Kolari (1979), Raitio (1983), and Will (1985).

Low foliar boron concentrations have been reported previously for lodgepole pine in the north-central Interior (Brockley and Yole 1985; Ballard 1986; Carter and Brockley 1987). Moreover, frequent boron applications are needed to sustain healthy growth of agricultural crops (B.C. Ministry of Agriculture 1978). Probable boron deficiencies have also been reported for a number of coastal Douglas-fir plantations (Carter *et al.* 1984; Carter *et al.* 1986). In Scandinavia, Scots pine and Norway spruce forests established on peatland commonly suffer from boron deficiency (Braekke 1979, 1983*a*; Veijalainen *et al.* 1984); on mineral soils, boron deficiencies may be induced or aggravated by nitrogen fertilization (Aronsson 1983; Braekke 1983*b*; Möller 1983*b*). However, research has demonstrated that growth

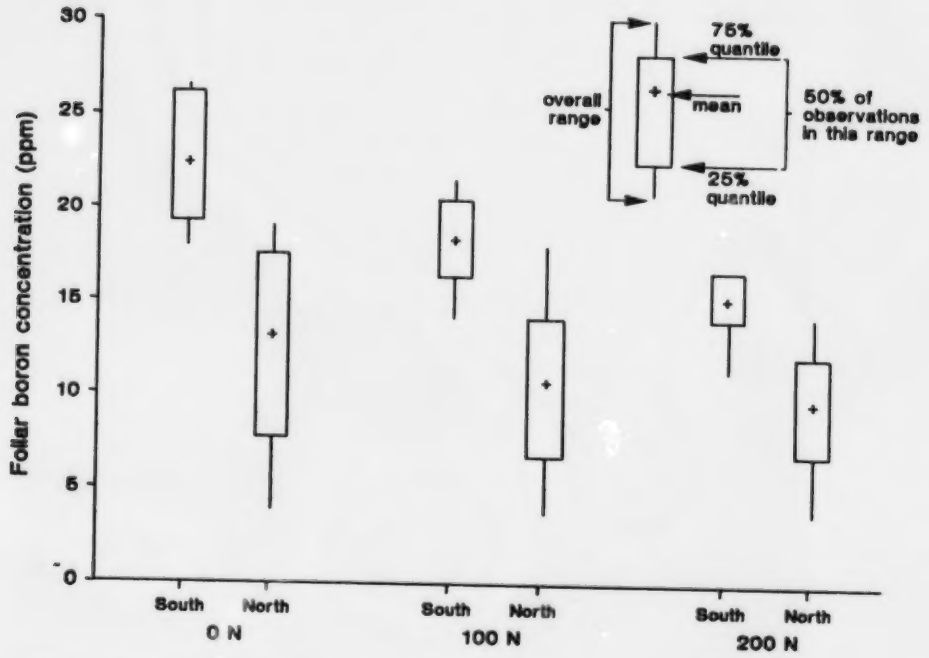


FIGURE 9. The effect of fertilization on foliar boron concentration 1 year following nitrogen application in installations located in the southern interior of British Columbia (n=4) and in installations in the north-central interior of British Columbia (n=7).

disturbances can generally be alleviated by boron application. In Sweden, it is recommended that boron be mixed with nitrogen when fertilizers are applied north of 60° latitude (Möller 1983b).

The role that inadequate boron nutrition played in limiting the responsiveness of other installations to nitrogen fertilization is difficult to establish since most boron-deficient stands are initially diagnosed on the basis of visible growth disturbances. However, it also seems likely that response potential to nitrogen fertilization may be reduced because of sub-acute boron deficiency. Marginal boron deficiency, suggested by Lambert and Turner (1977) to be in the range of 8-12 ppm for *Pinus radiata* D. Don in Australia, leads to the growth of more or less normal trees. Snowdon (1971) reported growth responses of *P. radiata* to boron with foliar levels up to 15 ppm. In this study, average initial foliar boron concentration was <15 ppm in 6 of the 11 installations (Table 14).

The precision of "critical" values for boron deficiency diagnosis is reduced by the considerable variation in boron concentration among foliage samples from the same installations in successive years (Table 14). Uptake of boron is primarily through mass flow of water to roots and is, therefore, strongly influenced by soil moisture (Mengel and Kirkby 1987). Periodic growing season water deficits, corresponding with the period of maximum shoot elongation and radial increment, may temporarily reduce the availability and/or uptake of boron. Unlike most macronutrients, boron cannot readily move from older to younger tissue within the tree. Hence, even brief interruptions in uptake can cause deficiency symptoms to develop quickly. Foliar boron concentrations and growth of affected trees may return to normal after soil water availability increases. Therefore, if boron deficiencies are to be avoided, levels of boron higher than 10 ppm are probably required in years when soil water availability is favourable. Additional research is needed to assess the boron nutrition of interior forests more adequately.

FIGURE 10. Top die-back following nitrogen fertilization in a lodgepole pine stand near Burns Lake, B.C. Visual symptoms and foliar boron concentrations are indicative of boron deficiency.

TABLE 14. Variation in mean foliar boron concentration (ppm) of unfertilized trees in the same installations in successive years

Installation No.	Initial	1st year	3rd year
1	25	20	18
2	17	18	17
3	17	26	17
4	13	26	17
5	12	16	17
6	4	8	12
7	2	4	9
8	17	18	18
9	10	19	13
10	16	18	17
11	8	10	15

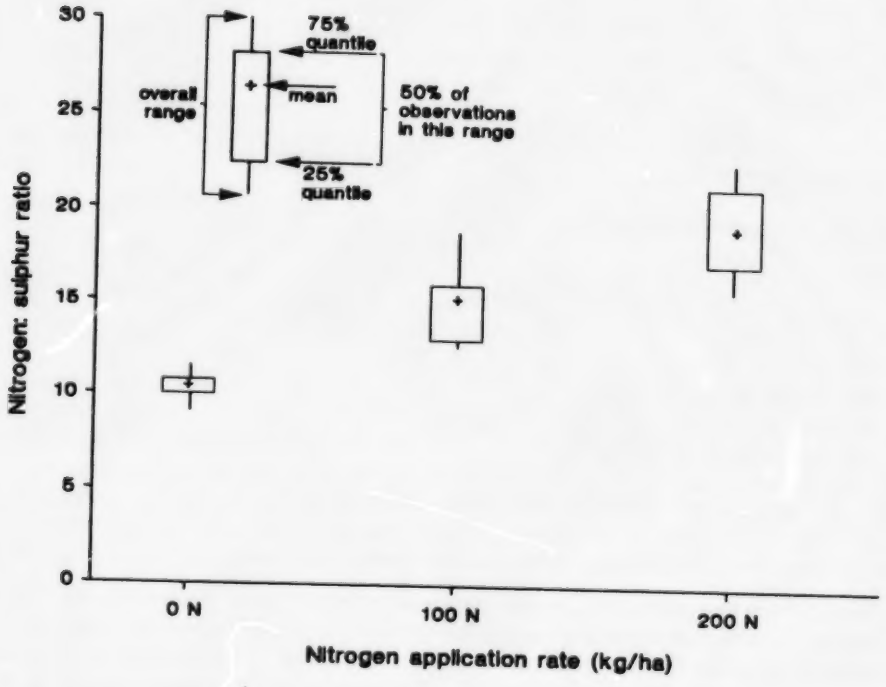


FIGURE 11. The effect of fertilization on foliar nitrogen:sulphur ratio 1 year following nitrogen application.

Despite the marginal sulphur status commonly encountered in many interior forests, sulphur deficiency is rarely diagnosed because a tree's sulphur demand is generally limited by nitrogen deficiency (Ballard 1986). However, it is often suspected that nitrogen fertilization may induce sulphur deficiency. Yang (1985*b*) reported that a combined application of nitrogen and sulphur was significantly better than nitrogen alone in improving the growth of 30-year-old lodgepole pine in Alberta. In north-central British Columbia, fertilizer treatments including nitrogen and sulphur resulted in greater 1st-year needle weight response than nitrogen fertilization alone when applied to an Age Class 3 lodgepole pine stand (Yole 1986).

Based on total sulphur and nitrogen:sulphur interpretations suggested by Ballard and Carter (1986), the initial sulphur status of all 11 installations examined in this study indicated actual deficiency or deficiencies inducible by nitrogen fertilization. Foliar nitrogen:sulphur ratio increased with increasing nitrogen application rate in all installations. One year following treatment, average nitrogen:sulphur ratio of fertilized trees exceeded the deficiency level (14.6) suggested by Ballard and Carter (1986) (Figure 11). Despite the large initial increase in foliar nitrogen:sulphur immediately following fertilization, ratios in the southern Interior generally soon returned to normal levels. However, in many installations in the north-central Interior, nitrogen:sulphur ratios in fertilized plots remained high after 3 years.

In the foliage of radiata pine and Douglas-fir, a constant ratio has been found between organic sulphur and total nitrogen (Kelly and Lambert 1972; Turner *et al.* 1977). Any sulphur in excess of that required to balance the nitrogen in protein formation is accumulated in the foliage as inorganic sulphate-sulphur. Addition of nitrogenous fertilizer to a stand results in partial utilization of this sulphate-sulphur reserve. Because a tree is unable to use added nitrogen effectively unless a sufficient sulphate-sulphur reserve is present, foliar sulphate-sulphur has been shown to be a much more sensitive indicator of the sulphur status of the tree and site than total foliar sulphur. Turner *et al.* (1977, 1979) found that Douglas-fir trees with high sulphate-sulphur levels responded well to nitrogen fertilization, whereas those with low sulphate-sulphur reserves responded poorly. In this study, foliar analyses undertaken at the time of the 3-year remeasurement indicate that in 6 of the 11 installations, average foliar sulphate-sulphur levels in unfertilized plots were below the deficiency level (i.e., 80 ppm) suggested by Turner *et al.* (1977). All but one of these installations were located in the north-central Interior. Foliar sulphate-sulphur levels in fertilized plots averaged only 40 ppm (range 9-67 ppm) and 25 ppm (range 7-44 ppm) for application rates of 100 N and 200 N, respectively. Turner *et al.* (1979) suggested these levels are not adequate to sustain tree growth. As with boron, more research is needed to assess the sulphur status of interior forests.

3.5.2 Small mammal damage

Red squirrels (*Tamiasciurus hudsonicus* Erxleben) have been clearly implicated as significant damaging agents in juvenile stands of spaced lodgepole pine throughout the interior of British Columbia (Sullivan 1985; Brockley and Elmes 1987; Brockley and Sullivan 1987; Sullivan and Vyse 1987). These animals peel and remove bark from the basal and sometimes upper sections of trees, which results in mortality or loss of vigour. Most damage occurs in late spring (May to July) during the early part of the growing season. Data indicate that fire-origin stands are more susceptible to barking damage than stands naturally regenerated following harvesting (Brockley and Elmes 1987). Fire-origin stands often cover extensive areas and surrounding mature timber may be a considerable distance away. The absence of readily available conifer seed may compel the resident squirrel population to feed on lodgepole pine cambium tissue until alternative food sources become available. Also, mustelid predators (e.g., marten, fisher, weasel) are more common in mature forests than in juvenile lodgepole pine stands.[4]

Results from this study indicate that improved palatability and nutritive quality may make fertilized, fire-origin lodgepole pine especially susceptible to red squirrel barking injuries (Figure 12), and thus agree with earlier findings by Sullivan and Sullivan (1982). Six of the 11 installations exhibited squirrel damage to crop trees 3 years after fertilization. In all cases, fertilized plots sustained more damage than unfertilized plots. The effect of nitrogen fertilization on the proportion of lodgepole pine crop trees damaged by red squirrels in installation No. 2 near Kamloops, B.C., is illustrated in Figure 13.

[4] Sullivan, T.P. Mammal Pest Management Ltd., Langley, B.C. Pers. comm., 1988.

FIGURE 12. Red squirrel barking injuries to fertilized lodgepole pine crop trees in installation No. 2, near Kamloops, B.C.

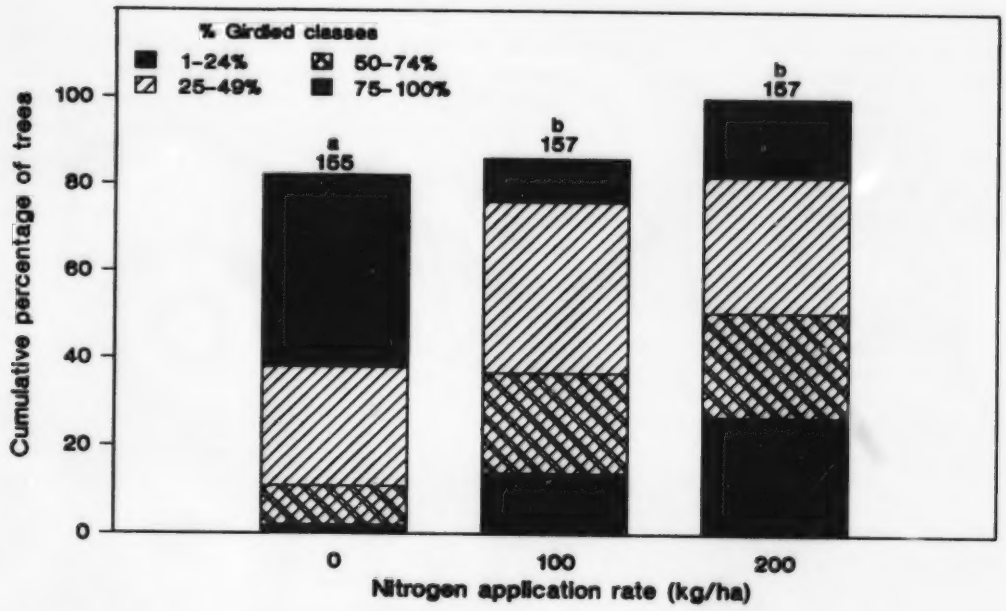


FIGURE 13. The effect of fertilization on the incidence and severity of red squirrel feeding injuries 3 years following nitrogen application (from Brockley and Sullivan 1988).

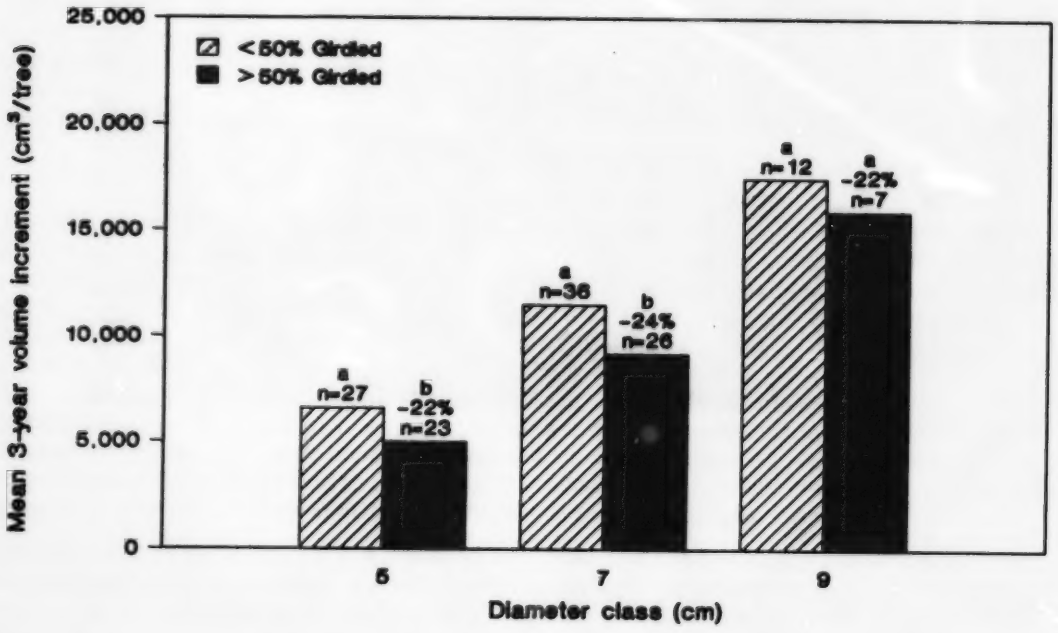


FIGURE 14. The effect of red squirrel feeding injuries on mean 3-year volume increment (cm^3/tree) following fertilization (200 kg N/ha) graphed by diameter class.

Three years following fertilization, squirrels had attacked significantly more trees in fertilized plots (95% and 99% for application rates of 100 and 200 N, respectively) than in unfertilized plots (81%). Moreover, fertilization clearly had a marked effect on the severity of damage wounds. Thirty-five percent and 49% of trees in 100 and 200 N plots, respectively, had wounds that girdled ≥50% of stem circumference. Only 11% of unfertilized trees exhibited injuries of similar severity. In fact, the majority of damage in unfertilized plots was confined to the 1-24% circumference girdled category. Outright mortality caused by complete girdling averaged 14% in the 200 N plots compared to only 1% in the unfertilized plots. In installation No. 5 near Prince George, B.C., squirrels removed 4.1 and 5.7 times the amount of bark from 100 N and 200 N stems, respectively, than from unfertilized trees. Because the probability of girdling is inversely related to stem diameter, squirrel damage generally had a greater negative impact on stands thinned at the time of fertilization (due to a smaller average crop tree diameter) than in adjacent, previously thinned installations.

Semi-girdling (sub-lethal) injuries represent a considerable physical impediment to the translocation of growth substances below the injury, and will undoubtedly negatively affect response to fertilization. The effect of barking injuries on the 3-year volume increment of fertilized trees is shown in Figure 14. Analyses of the effect of semi-girdling (i.e., >50% circumference girdled) on volume increment were restricted to those diameter classes that had sufficient trees of both damage classes (i.e., >50% and <50% girdled). Trees with semi-girdling injuries grew significantly slower than less severely damaged trees in the 41-60 mm and 61-80 mm size classes, representing 22% and 24% reductions in growth, respectively, over the 3-year response period.

Clearly, feeding injuries by red squirrels will adversely affect fertilization response through outright mortality caused by complete girdling, and through reduced growth increment from sub-lethal damage. These findings are consistent with results previously reported for hare damage to balsam fir (*Abies balsamea* [L.] Mill.) by Lloyd-Smith and Piene (1981) and lodgepole pine by Sullivan and Sullivan (1986).

Trees in small fertilized plots may be preferentially attacked by squirrels resident in the surrounding untreated areas, leading to over-estimation of the damage that would occur with more extensive, operational fertilization. However, these research data, combined with the high incidence of squirrel damage often observed within extensive thinned blocks (Brockley and Elmes 1987; Sullivan and Vyse 1987), indicate that operational fertilization may result in increased damage susceptibility.

3.5.3 Snowpress

Results indicate that stands thinned at the time of fertilization are more susceptible to snowpress damage (i.e., irreversible bending or breakage of bole) than those thinned prior to fertilization (Table 15). In fact, no damage was observed in the latter installation type. These findings agree with previous reports that thinning may initially reduce stand stability, and thus temporarily increase susceptibility to snow damage (Powers and Oliver 1970; Lines 1981). The fact that these excessively dense stands were thinned at a relatively late age probably contributed to the severity of damage. Stands of lower density and those thinned at an earlier age would presumably be less susceptible to snowpress damage.

Within damaged stands, the heaviest snow damage was associated with fertilized plots (Table 16), apparently due to the larger foliage biomass of fertilized trees which resulted in more accumulation of snow and greater resistance to wind. These findings are consistent with those of Miller and Pienaar (1973), Schnekenburger *et al.* (1985), Barclay and Brix (1985) and Cochran *et al.* (1986). Responsive stands appear to be especially susceptible to snowpress. In installation No. 4, 16% and 28% of trees fertilized at rates of 100 and 200 kg N/ha, respectively, were either leaning or down 3 years following thinning and fertilizing. None of the trees in the unfertilized plots were damaged. These losses all but wiped out per-hectare volume gains.

TABLE 15. A comparison of the number of trees damaged and undamaged by snowpress in installations thinned at the time of fertilization (Type1) and those thinned at least 2 years prior to fertilization (Type 2)

	Installation type		
	Type 1	Type 2	Total
Damaged trees	126	0	126
Undamaged trees	2601	2244	4845
Total	2727	2244	4971

Chi-square = 106.5 with 1 df; significant at $p<0.01$.

TABLE 16. A comparison of the number of trees damaged and undamaged by snowpress in installations thinned at the time of fertilization by treatment (kg N/ha)

	Nitrogen application rate (kg/ha)			
	0	100	200	Total
Damaged trees	15	50	61	126
Undamaged trees	897	863	841	2601
Total	912	913	902	2727

Chi-square = 29.2 with 2 df; significant at $p<0.01$.

4 CONCLUSIONS AND RECOMMENDATIONS

The short-term results obtained to date in this study are encouraging. Nitrogen fertilization has had a substantial effect on tree and stand increment, thus confirming the tentative nitrogen deficiency diagnoses for lodgepole pine indicated by foliar research and fertilizer screening trials. Results are consistent with numerous studies that have found nitrogen to be the element that most limits the growth of conifers throughout northern temperate and boreal forests. Average percentage gains compare favourably with those reported previously for lodgepole pine and jack pine within the glaciated region (Malm 1973; Boyd and Strand 1975; Bella 1978; Krause *et al.* 1982; Pettersson 1984; Yang 1985*a*, 1985*b*). The absolute volume gains reported by Yang (1985*a*, 1985*b*) for lodgepole pine and by Krause *et al.* (1982) for jack pine, although at times larger than those reported here, were achieved in older stands with considerably greater standing volume. Moreover, the most responsive treatments in these other studies often contained nutrients other than nitrogen. In this study, the favourable effects of fertilization were partially negated by treatment-related mortality. Although some losses might also be expected on an operational scale, they will undoubtedly be less severe than recorded in these small research plots.

The prospects are favourable for continued growth response in these thinned lodgepole pine fertilization trials. Due to the present lack of inter-tree competition, conditions are good for use of the improved growth potential resulting from increased foliage mass and photosynthetic capacity. However, accelerated stand growth and changes in stand structure from fertilizer application may affect the net yield gains obtained under the various density regimes used in this study. This aspect will be dealt with in a separate study, in which the relationship of stand density to long-term response to fertilization will be explored.

Differences in growth response between application rates of 100 and 200 kg N/ha were generally small over the initial 3-year response period. In many installations, however, foliar nitrogen concentration and/or unit needle weight in 200 N plots remained significantly higher than in 100 N plots 3 years after fertilization. Therefore, the dosage effect may increase over time because of a more sustained response to the higher nitrogen application rate.

Graphical diagnosis of shifts in needle weight and foliar nutrient concentration and content in the first growing season following fertilization generally corresponded with subsequent 3-year volume response. Therefore, where fertilizer screening trial response data are available, the foliar graphical diagnostic technique may represent a reasonably accurate "quick index" for evaluating the long-term volume response potential of candidate stands to fertilizer application. The technique may also provide rapid feedback regarding the relative responsiveness of operational blocks to aerial fertilization and may, in some cases, at least partially satisfy operational fertilization monitoring objectives.

Response to nitrogen fertilization was variable and the nitrogen status of a site, based on foliar nitrogen concentration and soil mineralizable nitrogen, was shown to be an unreliable predictor of the potential responsiveness of lodgepole pine to nitrogen additions. Eleven installations are obviously not sufficient to adequately explain this variation in response. A great deal more research is needed to identify and test relationships between various stand and site characteristics, nutrient deficiencies, and response to fertilizer treatments before site-specific guidelines for lodgepole pine operational fertilization decision-making can be developed. In the interim, however, the following recommendations can be made:

1. Until fertilization research data indicate otherwise, sulphur should continue to be added in conjunction with nitrogen when lodgepole pine forests are operationally fertilized within the interior plateau. In addition, boron should be added to the nitrogen/sulphur mix in areas where average pre-fertilization foliar boron concentrations are below 10-15 ppm. Marginal boron status is common throughout the central and northern portions of the interior plateau, especially on sites subject to periods of soil water deficit during the growing season.

2. The best method for preventing or minimizing red squirrel feeding injuries to crop trees is to confine operational fertilization to stands having a low hazard rating (based on a pre-treatment damage survey). Because the probability of girdling declines with increased stem diameter, fertilization of high risk stands should at least be delayed until crop trees are large enough to withstand damage wounds. The development of squirrel damage in operationally fertilized stands should be monitored over time.

3. Because fertilization at the time of thinning apparently increases the susceptibility of crop trees to snowpress damage, previously thinned stands should be assigned higher priorities for operational fertilization. Assuming canopies have not closed, there is no reason to suspect that previously thinned stands will not respond favourably to fertilizer application. This "adjustment period" will also enable red squirrel damage potential to be more fully evaluated before operational fertilization investment decisions are made.

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